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Electrical process tomography: seeing "without eyes" inside stirred vessels

MANN R.
(*Department of Chemical Engineering and Analytical Science, The University of Manchester, Manchester M60 1QD, UK*)
E-mail: reginald.mann@manchester.ac.uk

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Abstract: Body-scanning exploiting 3-D imaging has revolutionised diagnostics and treatment in medicine. Process engineers would like to be similarly able to image chemical process units in 3-D, but without the £multi-million price tag. UMIST and Leeds University have together, through the Virtual Centre for Industrial Process Tomography (http://www.vcipt.org), pioneered several electrical process tomography techniques and used them in a variety of applications. Illustrations are presented to show how electrical resistance tomography (ERT) has been developed for typical stirred vessels widely encountered in batch process manufacturing. The technique is potentially fast and inexpensive and capable of imaging both dynamic and pseudo-stationary processes. Examples from UMIST's two-tonne vessel will be presented for miscible tracer mixing, as well as gas-liquid and solid-liquid mixing.

Key words: Process imaging, Fluid mixing, Stired vessel
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INTRODUCTION

Stirred vessels are widely used in the chemical industry as fluid mixing devices. These vessels at manufacturing scale often have more than a passing resemblance to the beaker used in the chemical laboratory to gather information on chemical pathways and reaction kinetics. Such oversimplified scale-up, based on simple geometric similarity at the small and large scales, is supposed to greatly reduce the uncertainty in scaling-up for manufacture. This "empirical" approach is forced upon us because of the general lack of understanding of the behaviour of such deceptively simple fluid mixing units. Although it is difficult to distinguish cause and effect in this scenario, there is little doubt that our lack of understanding interacts with a failure to provide instrumentation that can both measure and monitor the "fluid mixing" on-line during typical batch manufacture.

Fluid mixing arises from complex interactions between the convective flow generated by the impeller/agitator rotation and the associated turbulence which has random eddies varying in size from the vessel dimension down to sub-micron. Turbulence is invariably present in low viscosity thin water-like fluids, but even at higher viscosities, a thicker more viscous fluid will show complications instead from non-Newtonian rheology, even though turbulence may be absent.

In chemicals manufacture, the effects of fluid mixing on the chemical pathway(s), hence the selectivity to desired product(s), is always indirect and arises via chemical species concentrations. Whenever the reactions are fast relative to rates of fluid mixing, there will always be a spatial "field" of concentrations in semi-batch operation. In this mode of operation, one chemical component is added from a feed reservoir to another already in the vessel. In this way, the rationing of one of the reagents controls reaction run-away hazards. However, this drip feed of one reagent when combined with the usual need to have reasonable production rates will invariably lead to non-uniform internal concentration fields. This in turn may have a complex effect upon the chemistry and spectrum of chemical products. It is therefore highly desirable to be able to quantify such concentration fields, which will always be three-dimensional for single point addition.

Unfortunately, our capabilities for "visualising" 3-D concentration fields inside a stirred vessel were until recently non-existent. Certainly, the classic approach using stimulus-response techniques (Levenspiel, 1999) is of no use for batch stirred vessels since they have no through-flow! The alternative approach seeks to use the mixing time, which is the time for a pulse injected material to become homogenised to some specific degree. However, as this is only a simple scalar measure of the rates of fluid mixing, it is of limited use for understanding the complex interactions of fluid mixing and chemistry.

This review will describe some recent developments in electrical resistance tomography (ERT) which have enabled us to begin to visualise mixing processes in 3-D inside a typical stirred vessel. ERT is inexpensive when compared to X-ray and MRI techniques developed for medical imaging. With ERT, the £-million price-tag for a body-scanner is reduced to a few £-thousand. In any case, this much cheaper technique is dominated by the cost of the associated electronics, since the sensor hardware can be made from simple metal plates wired together. The technique is effectively both non-intrusive and non-invasive and so does not interfere with the internal fluid mechanics.

THEORETICAL INSIGHT CONFIRMING INTERNAL SPATIAL NON-UNIFORMITY

Evidence for the existence of spatially distributed concentration fields has been accumulating for a number of years, earlier theoretical analyses being limited to 2-D axi-symmetry to reduce the computational burden (Mann *et al*., 1995). More recently, it has proved possible to compute in 3-D and some results are presented in Fig.1 for single phase miscible fluid mixing with single point addition of a component B from a feed reservoir to a component A initially placed in the vessel (Rahimi and Mann, 2001). Because there are two possible reactions of A, these predictions could also include chemical yield/selectivity. These computations use a simplified fluid dynamics based on networks of backmixed zones, which incorporates an overall rate of internal convective flow generated by the impeller rotation, a turbulent mixing parameter and a convective swirl (tangential) flow magnitude. In Fig.1, visual reality images are created based upon colouring each voxel according to its component concentration and ascribing to it an optical opacity also based upon concentration. What Fig.1 confirms is that there is predicted to be a distinctive plume of A (here showing red) spreading out from the addition point. By making use of a combination of forward perspective and overhead plan views, it is easy to visualise how the plume enlarges and swirls tangentially as the addition of B proceeds linearly over 15 s. The use of variable opacity allows an element of see-through, so that as the reagents disappear by reaction, the fluid becomes clearer (less opaque), and thus by 30 s, which is 15 s after completing the addition, the impeller has become partly visible. Predictions such as these need a visualisation technique like ERT, in order to validate the theory.

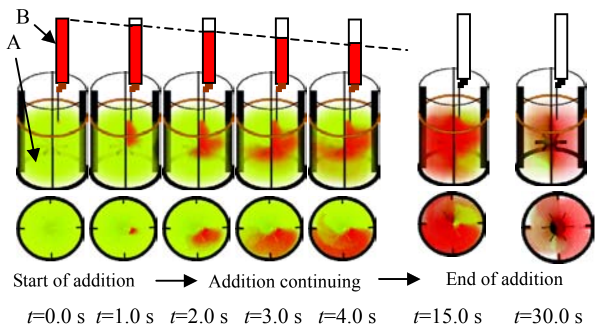

Fig.1 Segregated concentration fields inside a stirred semi-batch reactor

Similar effects can be expected for reactions which involve multiple phases and mass transfer. Thus Fig.2 shows an image of predicted two-phase gas-liquid mixing in which bubbles fed through a sparge ring will be dispersed and distributed by the radial flow pattern typically produced by a flat-blade or Rushton turbine (Williams *et al*., 1997). The bubbles are not uniformly dispersed throughout the liquid phase since they rise differently in upflow, downflow and crossflow. In particular, there are few bubbles in the lower part of the vessel, while a concentration of them is observed just above the sparge injection point. The pattern here is axisymmetric. It is evident that ERT, because of its capability to measure the local electrical conductivity should be able to detect and quantify this gas-voidage/hold-up field. If the gas and liquid each provide chemical components that can react, then the complex interactions of two-phase mixing and inter-phase mass transfer could give rise to regions rich in each component as shown schematically in Fig.3.

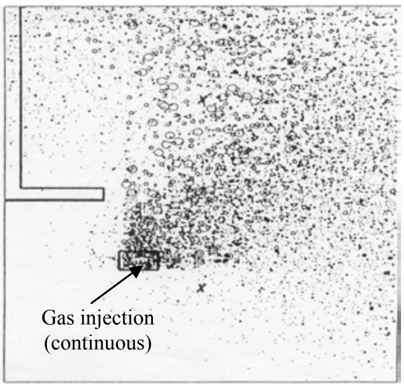

Fig.2 Non-uniform gas hold-up distribution in gas-liquid mixing

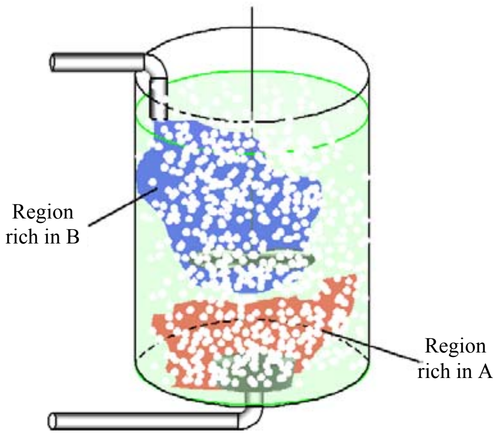

Fig.3 Segregated concentration fields for a gas-liquid reactor

Some predictions in 3-D have recently shown how dissolved oxygen and nutrient can be partially segregated in this way in a stirred bioreactor (Hristov *et al*., 2001; 2004). Fig.4 shows some predicted gas hold-up contours for a bioreactor fitted with three radial-flow Rushton turbines (Hristov *et al*., 2001). Once again, ERT can in principle visualise this type of behaviour, although now the technique needs to be able to be chemical species specific if the chemical species segregation is to be visualised in accordance with the schematic in Fig.3. Nevertheless, these three practical examples show the kind of internal visualisation needs of typical stirred vessels as used in the chemical industry.

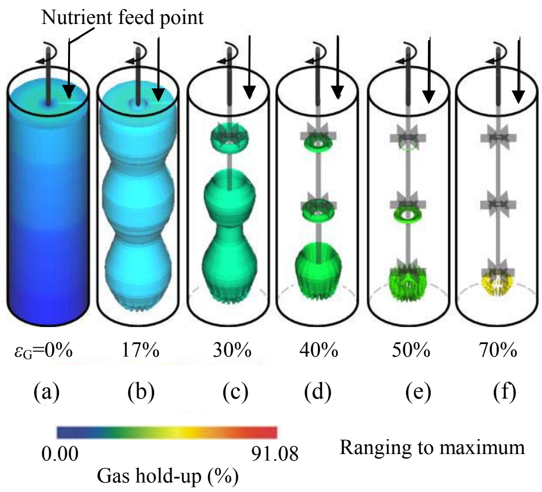

Fig.4 Predicted gas hold-up contours inside a bioreactor

PRACTICAL ERT SYSTEM FOR A PLANT-SCALE STIRRED VESSEL

A schematic view of the system installed on UMIST's two-tonne pilot plant vessel is shown in Fig. 5. The hardware forming the set of sensors is made up of 16 simple equally spaced rectangular stainless plates formed into a circular ring. There are eight such equally axially spaced rings as seen in the left part of Fig.5. The so-called interrogation protocol, in which current is injected and detected for the full set of combinations of injection/detection for each ring is set and executed by the data-acquisition system run by the PC. Signals returned from the DAS are passed to the PC, where they can be reconstructed into a tomogram for each of the eight circular planes. This system has been described in more detail elsewhere (Mann *et al*., 1997).

For a large number of measurements restricted to

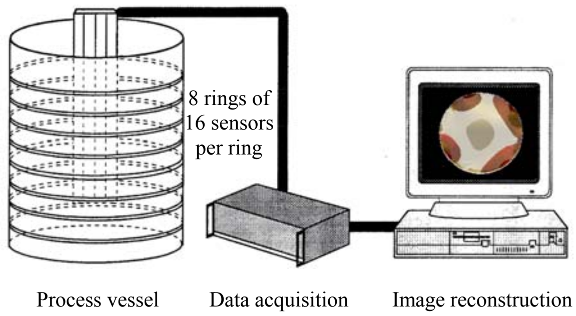

Fig.5 Schematic of electrical tomography for a stirred vessel

the outer periphery, the whole field can be covered and the interior values "reconstructed" from the set of peripheral values in the classic tomographic analysis. In this electrical process tomography, the interrogating paths are inconveniently non-straight, unlike X-rays. Reconstruction from such non-linear so-called "soft" fields is then less accurate, although simplified techniques like the simplest linear back-projection may still be capable of useful imaging of many processes. Finally, although this system neglects out of plane electrical effects, the set of eight tomograms can be "stitched" together to create a pseudo 3-D image.

SOME EXEMPLES OF STIRRED VESSEL TOMOGRAPHIC IMAGES IN 3-D MISCIBLE TRACER MIXING

In this section, some illustrative results from the 2-tonne vessel will be presented in brief. For each example, more complete details have been published elsewhere.

Fig.6 shows how the details of miscible fluid mixing can be captured over a few seconds, using a pulse injection of a highly conducting fluid (Holden *et al*., 1998; Mann *et al*., 2001). The point of injection of a brine tracer pulse is shown in the left hand pair of images at t=0. As before, the tomographic reconstructions are shown in pairs of images, with a forward perspective view on top and an overhead plan view below. The views at t=0 are blank. The ensuing electrical conductivity fields in time progression are then visualised as partial see-through assemblies of sets of solid-body contours coloured according to concentration. The intense high concentration red colour shrinks and fades as dilution takes place in three dimensions by fluid mixing. The green outermost boundary contour correspondingly enlarges as mixing proceeds, and the views show how the salt mixes through the impeller and undergoes clockwise swirling under the rotation of the impeller. It is important to recognise that although these images look like typical computational fluid dynamics (CFD), they are in fact experimental results. The 16-sensor× 8-ring array reconstructs 104 pixels for each of the eight planes, which in turn creates 832 pseudo voxels for the 3-D representation. Thus each image in Fig.6 contains $O(10^3)$ experimental points. Since the ERT system can acquire an image in about 0.3 s, 1 MB of mixing information is furnished in each 3 s.

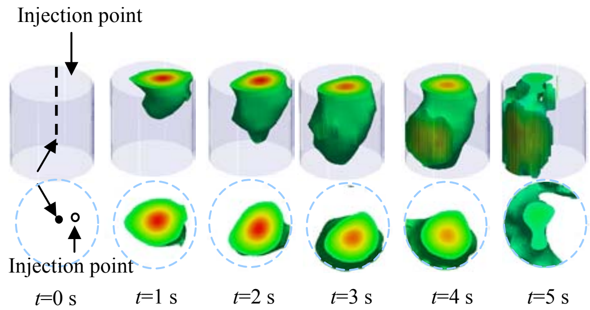

Fig.6 Miscible mixing of a brine tracer in 3D

GAS-LIQUID MIXING

One example image is presented showing how ERT can be used to visualise two-phase gas-liquid mixing. Fig.7 shows an experimental result for gas

Fig.7 Solid-body contours of gas hold-up for gas-liquid mixing

hold-up variation presented as three iso-surface contours. This image is for the type of situation predicted in Fig.2. Here regions of high/low conductivity can be detected, but not the individual bubbles. It is also not possible to say anything about variations in bubble size due to the limited spatial resolution of our ERT set-up. Fig.7 does show that the gas hold-up contours are approximately axi-symmetric, but there is some small random variation in the expected symmetry caused almost certainly by the "noisy" turbulent flow typical of such gas-liquid stirring (Mann *et al*., 1999; Wang *et al*., 2000).

SOLID-LIQUID MIXING

Finally, two examples of application to two-phase liquid-solid mixing are presented. In processes where the solid and liquid have differing electrical conductivities, ERT has the potential to image the distribution of solid when stirred with a liquid. This is frequently undertaken in manufacturing using stirred vessels. In this case we have imaged the suspension of non-conducting polypropylene particles of *mm* dimensions at low (1%) solid loadings. The nature of the behaviour is shown for illustration in Fig.8 using conventional visualisation in a lab scale glass stirred vessel filled with (clear) water. In Fig.8 the particles are black. Being denser than water they tend to settle out on the vessel base unless the stirring is sufficient to keep them fully in suspension. The left hand image shows a forward perspective view together with an underneath view gathered by placing a mirror beneath the vessel at 45 degrees. At the stirrer speed of 100 r/min, almost all the particles are formed into a symmetrical "hill" with some particles lifted up towards the impeller. Interestingly, the underneath view shows that the particles are not uniformly distributed across the base, but form heaps around the baffles, but with some portions of the base swept clean of particles. At the higher speed of 150 r/min in the right hand view, particles are better suspended and reach above the impeller. The base is still not uniform in deposited particles, although the self-obscuration by the suspended particles now makes it more difficult to see the clear portions of the base. However at both stirrer speeds, it is clear that the four vertical baffles introduce a 3-D effect.

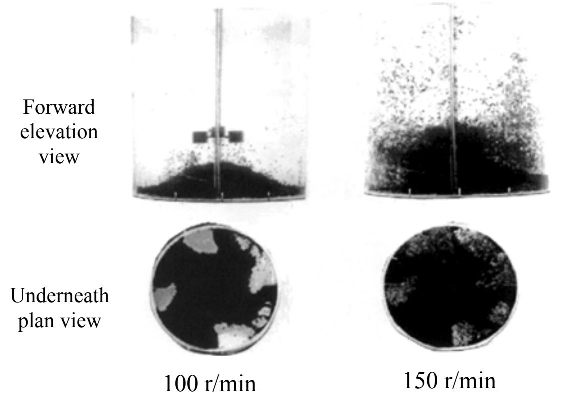

Fig.8 Optically visualised 3-D solid liquid mixing in a glass stirred vessel

Fig.9 shows how behaviour equivalent to normal visualisation in Fig.8 can be captured by ERT and image-reconstructed into 3-D images (Mann *et al*., 2001). These results are from the two-tonne vessel with 1% of the same solid polypropylene particles. In this visualisation we have retained a perspective forward view and an overhead plan view as before, but in this case interposed these with the forward elevation view, thus providing a set of three images at each pseudo-stationary solid-liquid mixing condition. Now, however, by converting the voxel conductivity values into solid content, as the particles have zero conductivity, we are able to map the solid distribution. Then in Fig.9, a set of three solid-content contours have been interpolated from the $O(10^3)$ voxels. An increasing degree of opacity between each contour has been ascribed to the intervening solid-content level, so that the highest level is fully opaque and below the lowest contour is perfectly clear. When the figure is constituted in this way, an augmented-reality image is generated which visually conveys the nature of internal solid suspension created by the impeller action. Thus in Fig.9, the darkest volumes belong to the highest solid-content, which is shown to lie behind the baffles on the downstream side (with clockwise impeller rotation). As the figure shows, as the impeller speed is increased, these highest density "pockets" of solid diminish in size. This is then balanced by the larger liquid volume at the intermediate solid level. This coincides with solid suspended at increasing heights above the base. These results therefore capture the full 3-D character of solid suspension in a way never before achieved. Moreover, it is important to stress that these ERT visualisations could be achieved even if the fluid in which the solids were being suspended were actually totally opaque, so nothing would be seen by the naked eye. It can therefore be reasonably claimed that Fig.9 represents seeing inside a stirred vessel "without eyes".

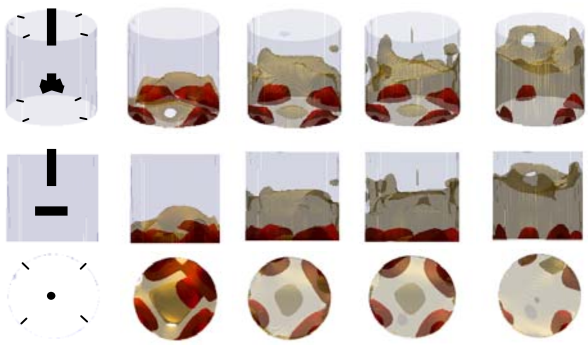

Fig.9 Tomographic 3-D visualisation of solid suspension inside a stirred vessel

Finally on an issue related to solid liquid mixing, we have obtained results for visualising semi-batch operation (Stanley *et al*., 2002). The arrangement is similar to that in Fig.1, but now if the reaction between the added reagent and the one already in the stirred vessel resulted in the precipitation of a solid product, it would be necessary to understand the composition field of the evolving plume. It has long been suspected that the "character" of the solid particles which nucleate and grow in the vessel will be sensitively dependent upon the local concentrations, supersaturation level and electrical conductivity. This is especially needed in the pharmaceutical industry, where the solid product must have a set of desirable properties that will engender good efficacy as a (often highly active and expensive) drug. It is hoped again that the augmented-reality imaging of semi-batch plumes will provide valuable assistance in understanding and quantifying the complexities of fluid mixing accompanying semi-batch precipitation.

CONCLUSION

Electrical resistance tomography provides a powerful means for non-intrusive measurement of fluid mixing processes inside typical stirred vessels.

Variations in conductivity enable 3-D visualization of miscible tracer mixing, as well as gas-liquid and solid-liquid mixing.

Solid-body graphics with opacity variation can create augmented-reality 3-D imaging.

Emerging developments will provide simpler techniques for better process imaging and reality augmentation.

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